

Measurements of b-jet Nuclear Modification Factors in pPb and PbPb Collisions with CMS

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Abstract

We present measurements of the nuclear modification factors R_{AA} and R_{pA}^{PYTHIA} of b jets in lead-lead and proton-lead collisions, respectively, using the CMS detector. Jets from b-quark fragmentations are found by exploiting the long lifetime of the b-quark through tagging methods using distributions of the secondary vertex displacement. From these, b-jet cross-sections are calculated and compared to the pp cross-section from the 2.76 TeV pp data collected in 2013 and to a PYTHIA simulation at 5.02 TeV, where these center-of-mass energies correspond to those of the PbPb and pPb data. We observe significant suppression for b jets in PbPb, and a R_{pA}^{PYTHIA} value consistent with unity for b jets in pPb. Results from both collision species show remarkable correspondence with inclusive-jet suppression measurements, indicating that mass-dependent energy-loss effects are negligible at p_T values greater than around 50 GeV/c. We use $150 \mu\text{b}^{-1}$ of lead-lead data and 35 nb^{-1} of proton-lead data collected at the LHC.

Keywords: QGP, b jets, energy-loss

1. Introduction

Quenching of jets in heavy-ion collisions is expected to depend heavily on the mass of the fragmenting parton. Under the assumption that gluon radiation is the dominant energy-loss mechanism, jets from heavy quarks are expected to radiate less due to the “dead-cone effect”, especially when the parton p_T is comparable to the parton mass. It must be said, however, that the mechanisms for in-medium partonic energy-loss are still poorly constrained. These measurements of the energy loss observed in jets from heavy-ion collisions as a function of jet flavor provide powerful constraints on the understanding of possible energy-loss mechanisms, as jet flavor is a direct proxy for the different parton masses. This analysis will focus on b-jet energy loss.

CMS is described in detail in the original detector publication [1], and its silicon tracker and hadronic calorimeter are excellent experimental tools for observing heavy flavor jets in heavy-ion collisions. Jets formed from heavy flavor quark fragmentation are typically tagged in one of two ways: first, by the direct reconstruction of a displaced vertex, and second by the displacement of individual tracks. Using the track-only tagging method as a cross-check ensures the secondary vertex reconstruction selections remain unbiased. The three-dimensional distance of the closest track point to the primary vertex is defined as the impact parameter [2]. Information from these tracks and vertices are typically combined into a quantity which optimizes their discrimination between heavy and light flavor jets. In this analysis, we use a discriminator to tag b jets which is based on the displacement of the reconstructed secondary vertex (SV) with respect to the primary vertex of the interaction. This discriminator is called the Simple Secondary Vertex tagger (SSV) [2], and is based on the displacement significance (displacement divided by its uncertainty) of

¹ A list of members of the CMS Collaboration and acknowledgements can be found at the end of this issue.

reconstructed secondary vertices. Detailed studies of quantities related to secondary vertex reconstruction show that the SSV tagger is well-modeled by both PbPb and pPb simulations, which means that it ought to perform well in both collision species. The efficiency of this SV tagging is then evaluated both directly from simulation, and with a data-driven method using a discriminator derived from an impact parameter-based method. This impact parameter tagger is only weakly correlated to the secondary vertex tagger and therefore provides a reliable way to evaluate the efficiency and purity of the SV tagger directly from data. Another discriminating variable, called Jet Probability (JP), takes advantage of this impact parameter tagger. The JP algorithm orders jet-associated tracks based on their impact parameter significance and calculates the likelihood that they come from the primary vertex [2]. The less likely that tracks originate from the primary vertex, the more likely they stem from a long-lived jet seed. The advantage to the JP algorithm is that it provides a measure of discrimination for nearly all b jets, even in the case when no secondary vertex is reconstructed. This property of the JP tagger is exploited to obtain a data-driven estimate of the SSV tagging efficiency [2].

The performance of lifetime-based tagging relies on the high efficiency and low fake rate of reconstruction of charged particle tracks from displaced vertices. In proton-lead collisions, the event multiplicity is low enough so that every track can be iteratively reconstructed, but this is not the case in lead-lead collisions. Due to timing and memory constraints, the standard heavy-ion tracking algorithm [3] in CMS is largely restricted to the reconstruction of charged particles from the primary vertex. Therefore, to enhance the efficiency of track reconstruction from secondary vertices, an additional reconstruction method is used. This “regional tracking” algorithm uses reconstructed jets as seeds and limits the search window for tracker hits to a region defined around the jet axis. Once reconstructed, the tagging performance is typically benchmarked by finding the b-jet tagging efficiency as a function of the light (udsg) jet and charm jet misidentification rate, such that the resulting curves are independent of the underlying b-jet fraction. The performance of the b-tagging degrades somewhat with the increased multiplicity of PbPb collisions, giving roughly a factor of three poorer rejection of light jets for a b jet efficiency of 50%, relative to a PYTHIA simulation alone. Despite the reduced performance, one is still able to achieve roughly a factor of 100 rejection of light jets for a b jet efficiency around 50%. The charm rejection for this b jet efficiency is about a factor of 10.

The b-jet yield in each p_T bin is obtained via equation 1, where f_b denotes the purity of the sample after b-tagging, ϵ_b refers to the efficiency of the b jet tagger, and N_{all} is the total number of jets in the sample.

$$N_b = N_{all} \frac{f_b}{\epsilon_b} \quad (1)$$

These purity and efficiency quantities are obtained by fitting to MC templates and cross-checked against the b-jet purity and efficiency found by using the JP tagger. For the purity, distributions of the secondary vertex mass in MC are fit to those obtained in data, where the fractional contribution of each jet flavor is allowed to float. Contributions from all three flavor types are comparable, but above about 2 GeV/c² (which roughly corresponds to the charm quark mass), the jet sample is dominated by b jets.

The efficiency (ϵ_b) is obtained via simulation, and is cross-checked using the JP tagger, as described above. Distributions of the JP tagger discriminator are obtained both before and after applying the SSV-tagged selection, as a function of jet p_T . In practice, we find the difference between the data-driven and MC ϵ_b value is about 5%. This difference is taken as a systematic uncertainty.

Finally, the b-jet yield is unfolded via the D’Agostini iterative procedure [4], as implemented by the RooFit statistical modeling toolkit. Once unfolded, the PbPb (pPb) data is scaled by a Glauber scaling factor “ T_{AA} ” (“ T_{pA} ”), in order to compare directly to pp data (simulation) [5]. The values of T_{AA} and T_{pA} are the number of nucleon-nucleon collisions divided by the total inelastic cross-section, and can be interpreted as the pp-equivalent luminosity per heavy-ion collision. These b-jet cross-sections are shown in figure 1 for various centrality selections in PbPb (left) and for various pseudorapidity selections in pPb (right). Also shown is the measured b jet cross-section in pp collisions as well as simulations from the PYTHIA Z2 tune [6], which agree well with the data. The pp luminosity measurement has an uncertainty of about 3.6%, while the uncertainty in T_{AA} varies from 4% to 15% as a function of centrality.

Figure 2 shows the measurements of b-jet R_{AA} (left) and R_{pA}^{PYTHIA} (right). A comparison of these two plots shows that the suppression effects for the PbPb plot are significantly greater than those observed in pPb, which indicates that initial state effects are not responsible for the suppression. In fact, as all R_{pA}^{PYTHIA} values are greater than one, indications of a small enhancement may be drawn. It is likely that any enhancement seen in pPb collisions stems from the Cronin effect, where multiple scatterings lead to an enhanced jet production from that observed in pp collisions.

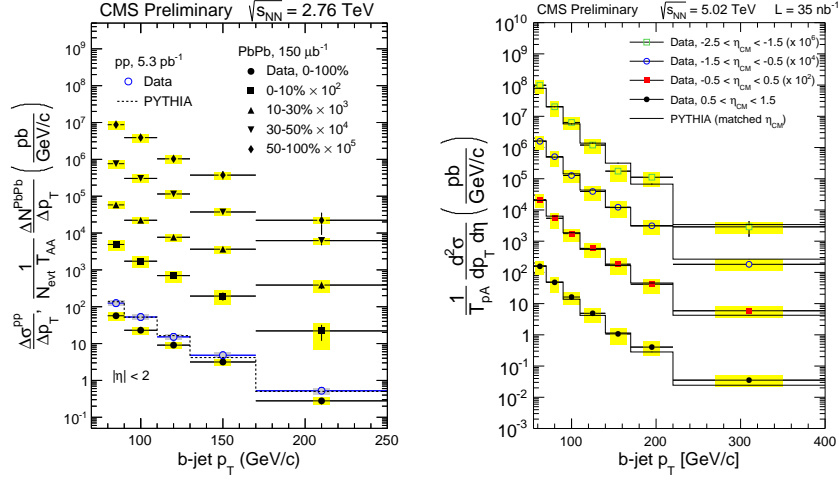


Figure 1. b-jet spectra as a function of jet p_T in bins of centrality for PbPb (left), and in bins of pseudorapidity for pPb (right)

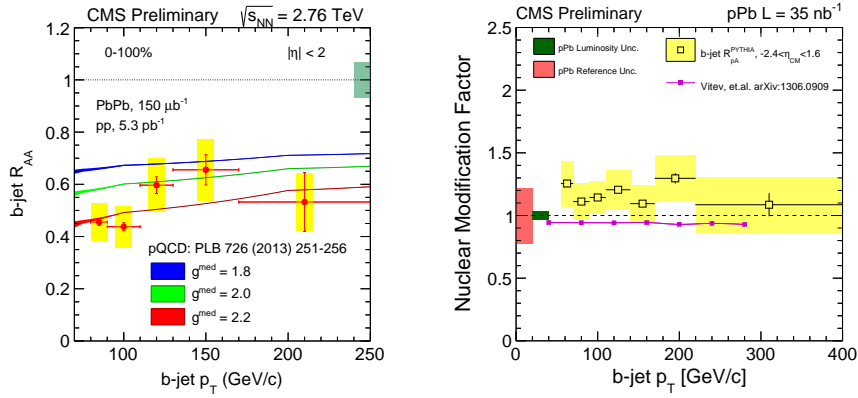


Figure 2. Centrality integrated b-jet R_{AA} as a function of p_T (left) and R_{AA}^{PYTHIA} (right). The filled green box denotes the normalization uncertainty from the integrated luminosity in pp and the T_{AA} in PbPb, while the filled red box denotes the uncertainty from the pp PYTHIA simulation used in the R_{pA} calculation. Theoretical predictions are from [7].

This also seems to be the case when a comparison is made to a theoretical prediction from Vitev et. al. [7], which is a calculation made in a perturbative QCD framework and an identical jet reconstruction algorithm. This prediction is shown as the purple curve just below unity in Fig. 2.

Finally, Fig. 3 shows measurements of both R_{pA}^{PYTHIA} and R_{AA} as a function of p_T for both the b-jets [8, 9] and the inclusive jets [10, 11], as denoted in the legends. We observe a very consistent result between the flavored jets and the inclusive-jet measurements, indicating that the suppression effects in PbPb collisions and enhancement effects in pPb are roughly parton-mass independent at very high p_T .

2. Conclusions

B jets in PbPb are found to be suppressed over a wide range of p_T , from 80-250 GeV/c. Furthermore, the R_{AA} value is found to decrease with increasing collision centrality. The b jets observed in pPb show virtually no suppression effects and may show possible hints of a Cronin enhancement due to cold nuclear matter effects. This lack of suppression is consistent within uncertainties across a wide range of p_T and pseudorapidity. Measurements as a function

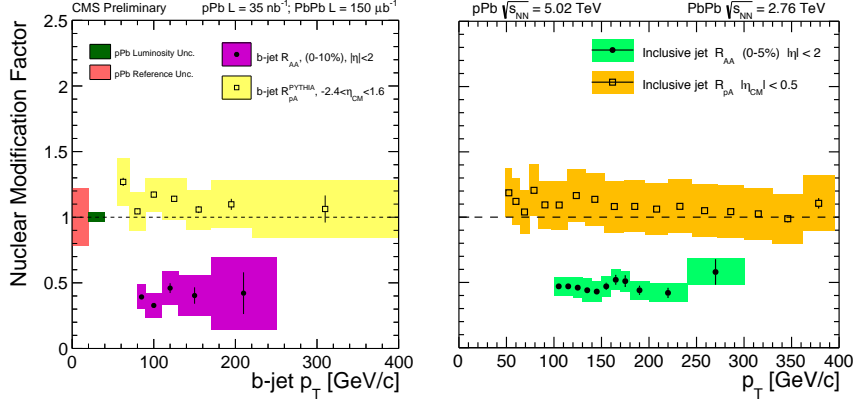


Figure 3. Nuclear modification factor comparison for b-jet R_{AA}^{PYTHIA} and R_{AA} (left) and inclusive-jet R_{AA}^{PYTHIA} and R_{AA} (right). The R_{AA} values shown are for 0–10% centrality, while the R_{pA} values are for inclusive-centrality. Note the similarity between both the R_{pA} and R_{AA} curves between the b-jet and inclusive-jet data.

of pseudorapidity may have implications regarding the suppression effects as a function of the Bjorken- x value of the incident parton in the lead nucleus (see [12] for further details).

In the end, the data presented in this analysis shows two striking features. First, the b jet production is clearly suppressed in PbPb collisions, while the production in pPb collisions is consistent with that calculated in pp simulations. Second, the data shows that the respective b-jet nuclear modification factors of both PbPb and pPb are very consistent with those seen in the inclusive-jet studies from CMS. From these observations, we can draw two conclusions: first that the suppression effects observed in PbPb collisions are not part of initial state effects, since the pPb nuclear modification factor is strikingly different than that observed in PbPb. Second, the jet suppression effects are essentially mass independent at very high p_T . These effects favor a perturbative energy-loss model where these mass-dependent effects are expected to be small, and are in contrast to an AdS/CFT inspired model where such effects can be quite large, even at very high values of p_T [13].

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